REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188,) Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	5/31/02	FINAL 6/1/99 to 5/31/02

4. TITLE AND SUBTITLE

Electronic Wavefunction Imaging and Spectroscopy in Metallic and Magnetic Nanostructures by Millikelvin Scanning Tunneling Microscopy

5. FUNDING NUMBERS

[redacted]DAAD 19-99-1-0254

6. AUTHOR(S)

Prof. J. C. Séamus Davis & Prof. Paul L. McEuen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Physics
University of California
Berkeley CA 94720-7300

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

40005.1-PH

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Our research group is involved in the use of a millikelvin Scanning Tunneling Microscope (mK-STM), developed in previous grant periods.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20030604 104

Final Progress Report G FDDAAD 19-99-1-0254

Foreword

We use high resolution STM at millikelvin temperatures (mK-STM) for allow imaging, spectroscopy, and control of the quantum wavefunctions of the electrons in metallic nanostructures. This work is directed at expanding our understanding of the quantum physics of electrons in metallic nanostructures, of effects of electron correlation in important materials, and of dopant atoms in semiconductors for the realization of quantum computing.

Statement of Problem

To develop a millikelvin STM capable of operation at high-fields with atomic-resolution spectroscopic mapping and its application for wavefunction imaging studies of important systems and to apply this technology to wavefunction imaging studies.

Summary of Achievements

1. Millikelvin STM Development

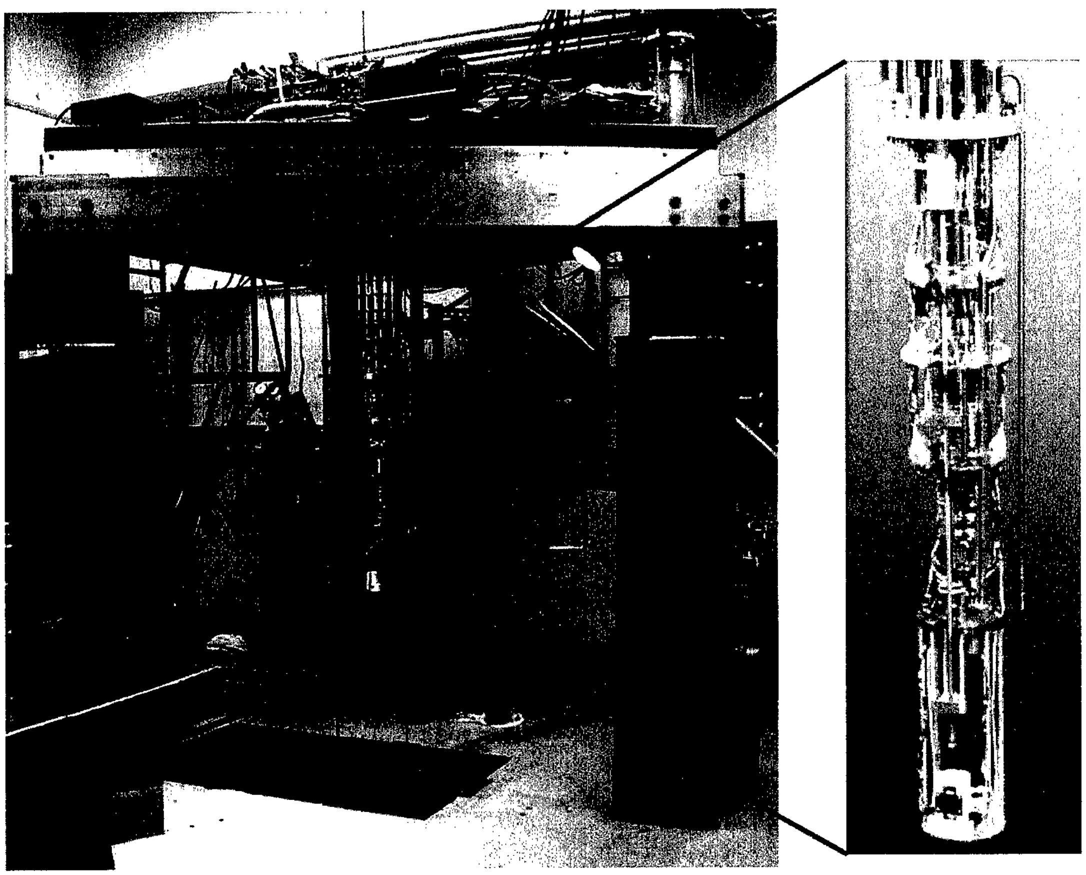


Fig.1a. Picture of the vibration isolation cryostat including the dilution refrigerator with STM head suspended below the mixing chamber.

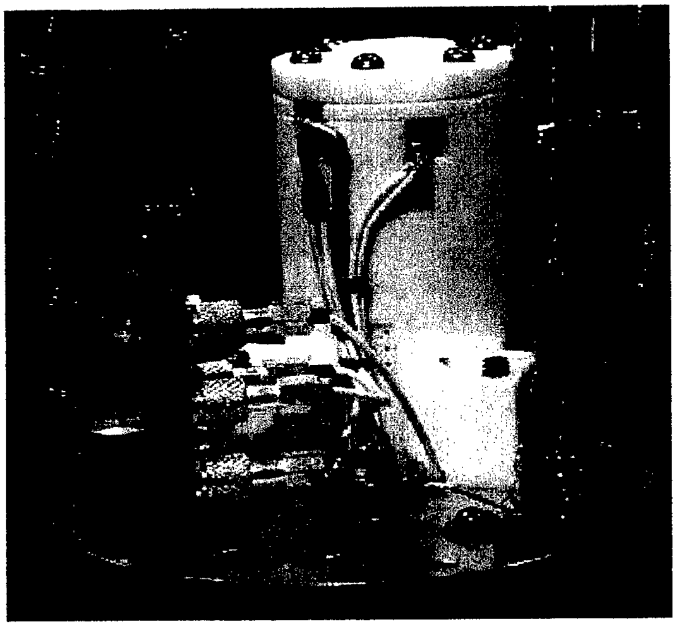


Fig. 1b. The STM head suspended below the mixing chamber.

The first achievement was successful development of a system (Fig. 1a and 1b) that allows atomic resolution spectroscopic mapping STM at temperatures down to 12mK in fields up to 9 Tesla. This is the only system of this type in the world.

2. Sr_2RuO_4

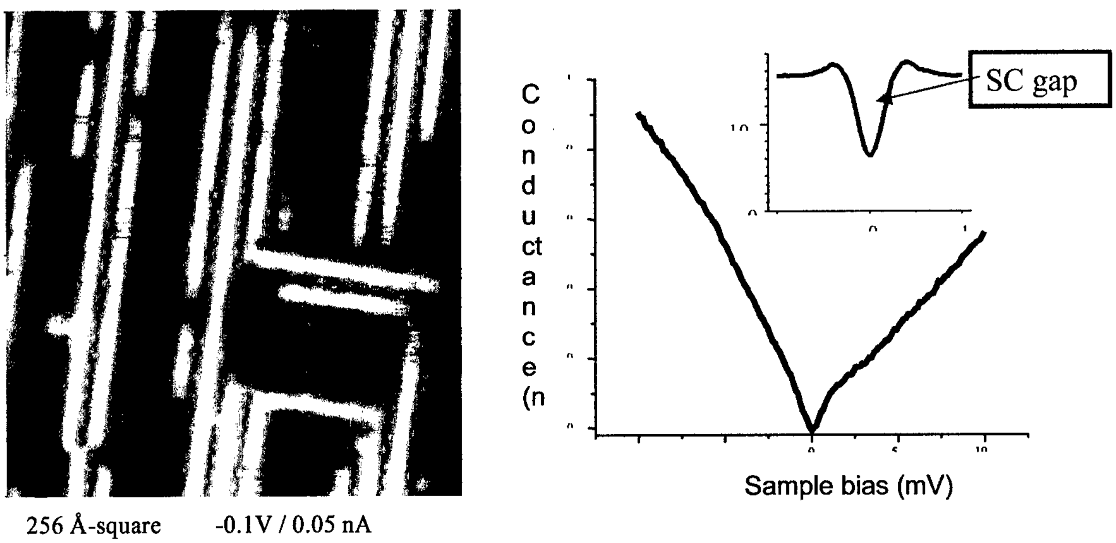


Fig. 2a. Image of the RuO surface of Sr_2RuO_4. b. Spectra on this surface showing the superconducting quasiparticle spectrum (insert).

We used the system for atomic-resolution scanning tunneling spectroscopy to study the spectrum of quasiparticle states in superconducting Sr_2RuO_4. This material displays an exotic form of superconductivity at temperatures below 1.45 K. As a result of extensive studies, both experimental and theoretical, a model for the p-wave symmetry of the superconducting order parameter (OP) is beginning to emerge. Because of the independence of the spin susceptibility on temperature below T_c, the Cooper pairs are believed to be in a spin triplet 'equal spin pairing' (ESP) state. Muon spin rotation studies show a time-reversal-symmetry breaking (spontaneous magnetization) signal which is also consistent with spin-triplet superconductivity. The temperature dependence of the quasiparticle spectrum, which we measured here for the first time, is consistent with a superconducting order parameter exhibiting a line of nodes. Further, in magnetic fields $H<H_{c2}$, a vortex lattice, square and oriented parallel to the <110> of the RuO_2 lattice, is detected by spectroscopic imaging. Each vortex exhibits one flux quantum, with a rotationally symmetric core and a strong zero-bias conductance peak.

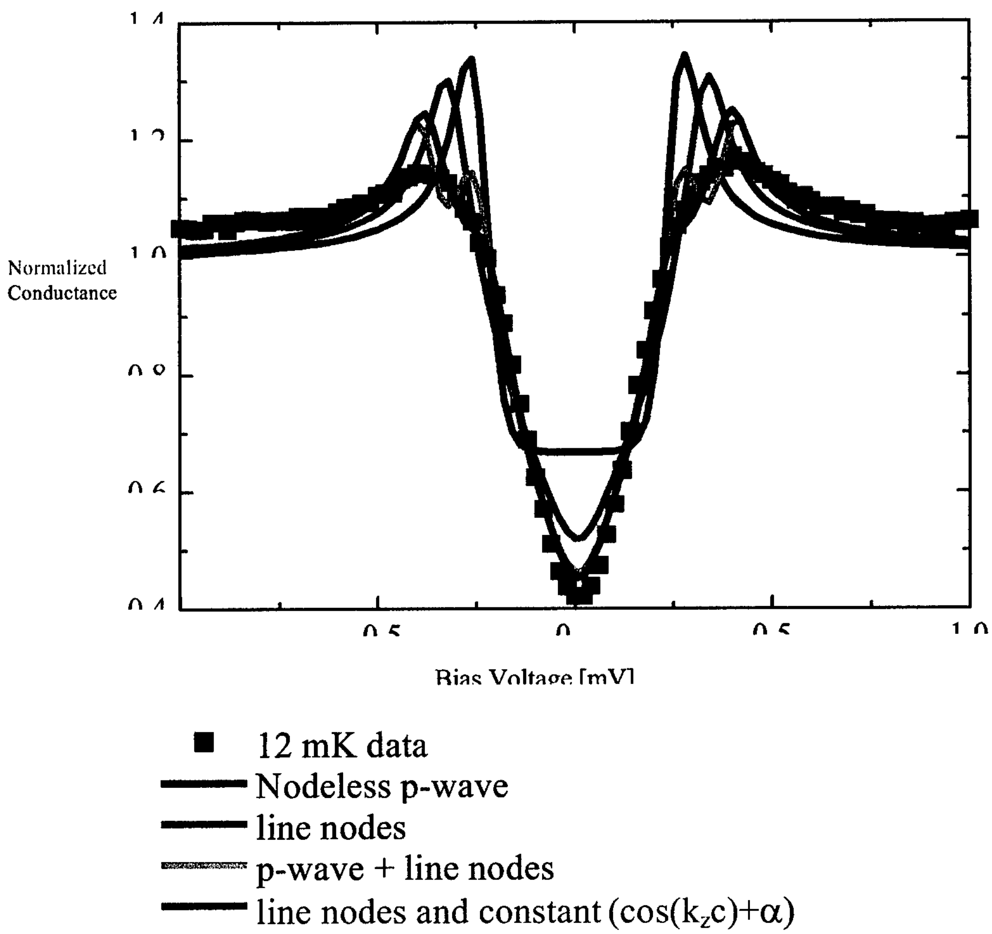
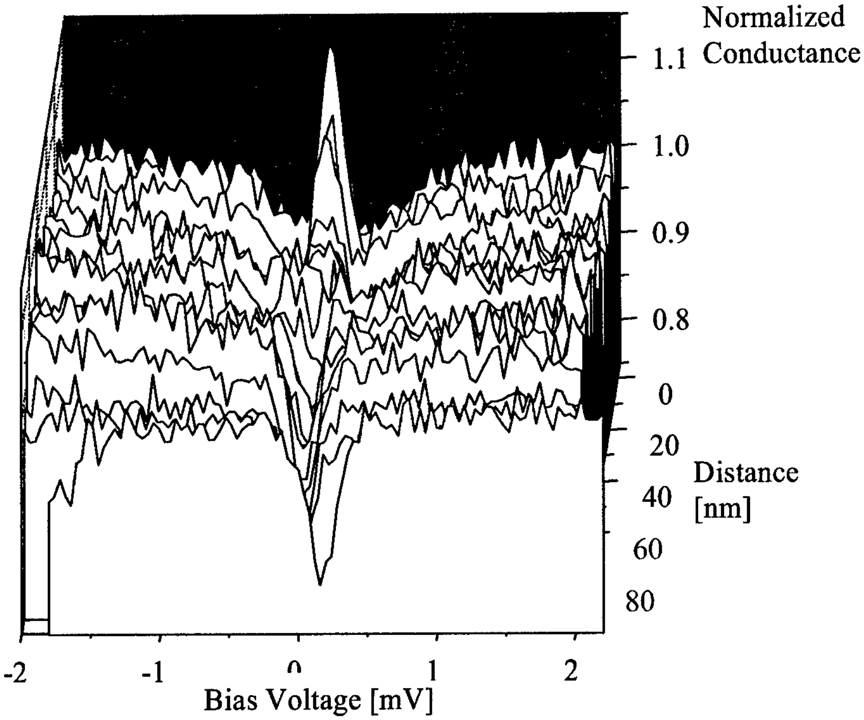


Fig. 3. Comparison of different model fits to tunneling spectra of Sr_2RuO_4 at 12 mK. Horizontal line nodes in momentum space appear to be the best fit.

Fig. 4. Dependence of spectra on distance measured form the center of a vortex core.



3. GaAs

We used the millikelvin, high-field, scanning tunneling microcopy (STM) to study the fundamental physics of bound electronic states at individual dopant atoms in a semiconductor. Although much has been said and written about electronically addressing single quantum states at dopant atoms in semiconductors, no experiments have been carried out and almost nothing is known about the applied physics of this situation. Therefore our studies were initially directed towards direct detection and study of the Zeeman-split bound-states at individual dopant Te atoms (in high magnetic fields at very low temperatures) as a test case. We could identify the location of the dopant atoms, measure their spectrum and locally map the wavefunction of the donor state with spectroscopic mapping.

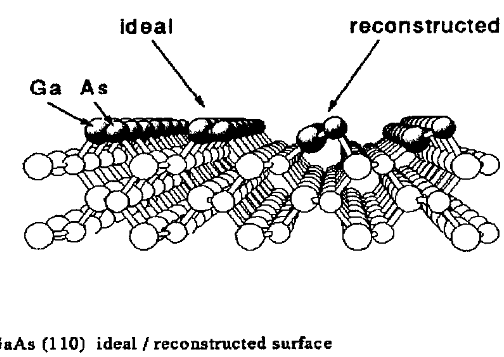


Fig. 5. Schematic of <110> cleave surface of GaAs

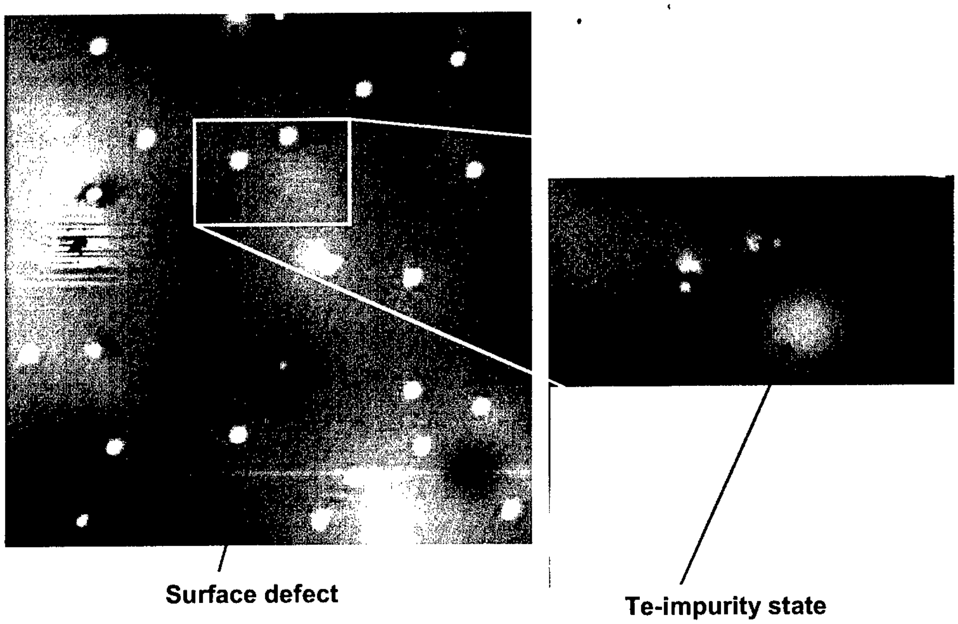


Fig. 6. Images of <110> surface of GaAs showing surface electronic defect states and the location of the Te donor atom.

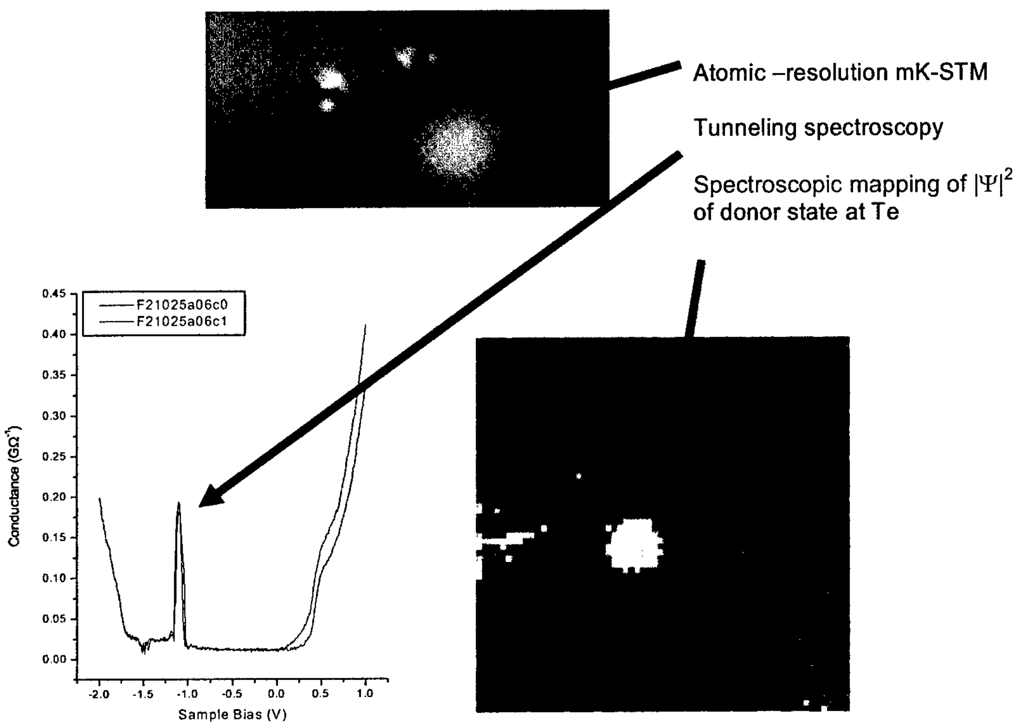


Fig. 7. Combination topographic image, spectrum at the Te site, and wavefunction image of the Te donor state (taken at 25 mK).

3. $NbSe_2$

This is a low temperature superconducting system with almost perfect atomic surfaces. We intercalate magnetic impurity atoms (Fe) between the planes and then, when we cleave it, they remain on the top surface. We can manipulate these atoms to make magnetic nanostructures whose electronic wavefunctions we are now studying by spectroscopic mapping at mK temperatures.

Topography+ Vortices

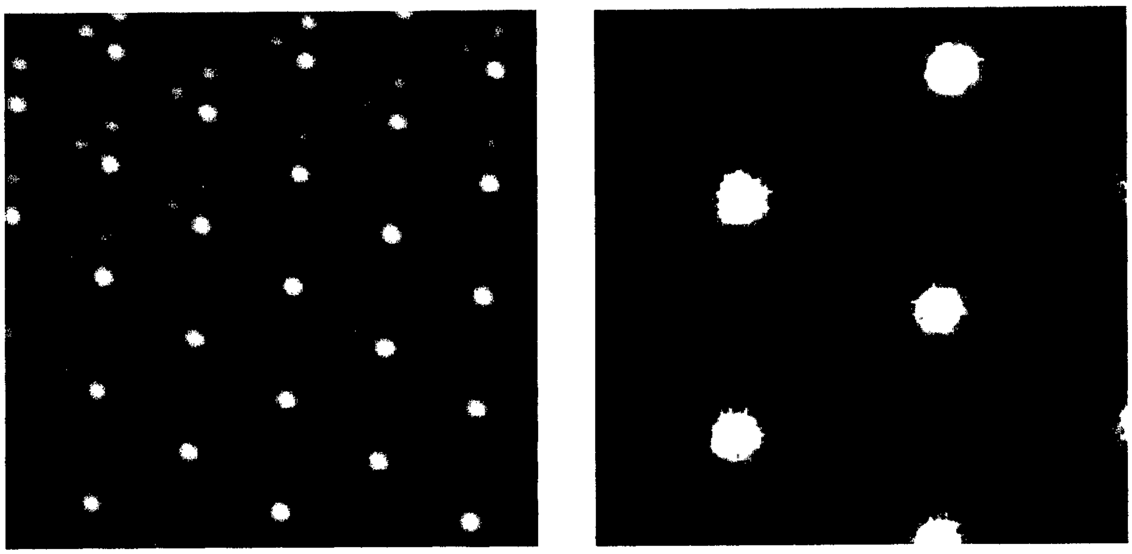


Fig. 8. a 250 Å square topographic image of the Se surface of NbSe2. Each Se atom, plus the charge density wave modulations, are seen. b. Wavefunction image of the vortex core states in a 1200 Å FOV at B~2 tesla.

CDW + Fe atoms

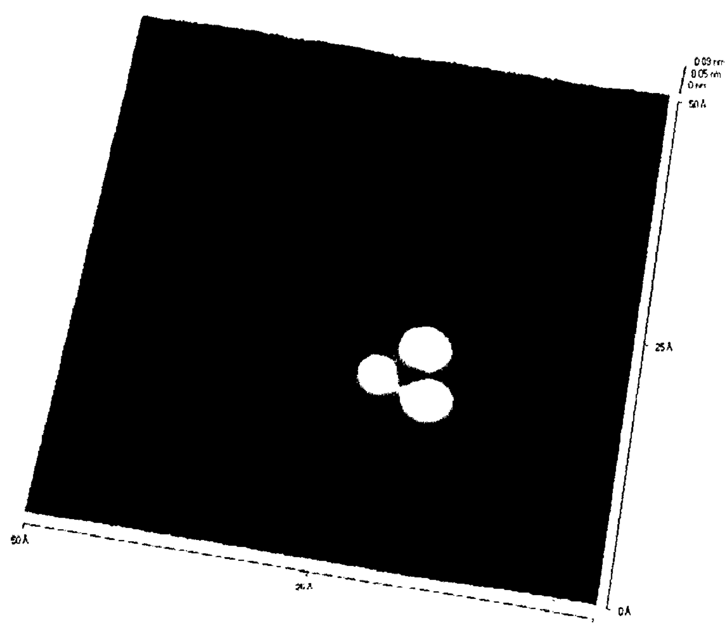


Fig. 9. A magnetic cluster of 3 Fe atoms assembled on the $NbSe_2$ surface.

Publications

1. "Effects of Individual Ti atoms substituted for Sr in Sr_2RuO_4" B. Barker, S. Dutta, C. Lupien, Y Maeno, and J. C. Davis, *submitted to Proceedings of LT23, Physics B.*
2. "Temperature- and Field-dependence of the Quasiparticle Spectrum of Sr_2RuO_4" C. Lupien, B. Barker, S. Dutta, Y. Maeno and J.C. Davis, *Submitted to Phys. Rev. Lett.*
3. A millikelvin high field spectroscopic mapping STM, B. Barker, S. Dutta, C. Lupien, and J. C. Davis, Submitted to *Rev. Sci. Inst.,*
4. Switching of the electronic configuration of defect states on the surface of GaAs, B. Barker, S. Dutta, C. Lupien, Y Maeno, and J. C. Davis, *in preparation.*

Personnel

Dr. Barry Barker (now at LPS, University of Maryland, College Park, Maryland).
Dr. Christina Lupien (moving to Cornell University to my new lab in June 2003).
Sudeep Dutta.
Rob Johnson. BSc 2003